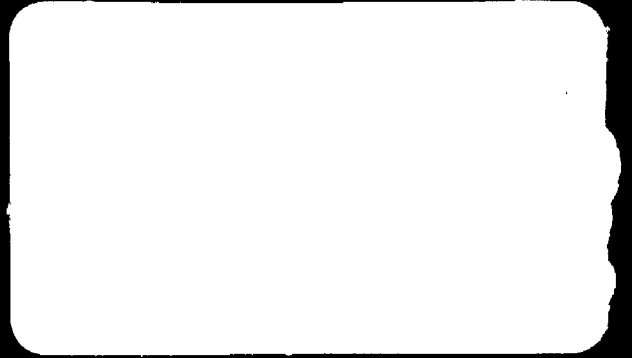


STENTOR 



Quad-Path Diversity
Digital Radio Systems

Stentor Resource Centre Inc

October 1993

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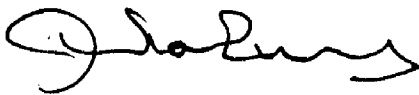
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SUBJECT: Quad-Path Diversity Digital Radio Systems

The attached document describes a method of building digital radio systems that can provide data performance that is two orders of magnitude better than that which can be achieved by conventional 2-path space diversity designs. Radio systems that use quad-path diversity can operate essentially error-free in the presence of severe fading. We believe that this report will be of interest to system designers and network planners within the Stentor owner companies.

We welcome your comments, as these will help to improve the quality of our documents and develop future documents that meet your needs. Please address these to me at the above address. If you would like to discuss the material in detail, please contact Dave Shimozawa at (604) 432-4630.



Attachments

Quad-Path Diversity
Digital Radio Systems

Stentor Resource Centre Inc

October 1993

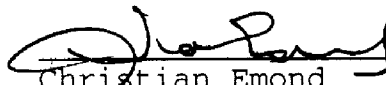
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EXECUTIVE SUMMARY

Radio systems provide high immunity to structural failures and natural disasters without the need for route diversity. They fit naturally with rugged terrain and are relatively easy to harden against vandalism or sabotage. For these reasons, digital microwave radio will continue to be an attractive alternative wherever the cost and risk of using other technologies are prohibitive.

The role however, of digital radio in the network is changing. There is now less dependence on radio technology to provide the raw bandwidth needed for long haul high capacity transport. That need is being met to an increasing extent by fibre optic systems. Also, there is a growing need to improve the data integrity of digital radio systems in the presence of atmospheric fading and to make these systems transparent to the end user during these events.

Quad-Path diversity radio systems are well suited for this changing role. These systems transmit the payload data from two separate antennas and carry it over four separate radio paths. As a result, they can provide near-perfect data transmission at moderate capacities over long paths under the most severe fading conditions. They also offer exceptional immunity to antenna system failures.

In this report, quad-path diversity systems are described and the required equipment characteristics are identified.

A method to predict the expected outage is developed. This prediction method is then applied to two examples of very difficult path designs. The first example is a working 122 km overwater reflective path at 6 GHz. The second example is a hypothetical 70 km land path at 4 GHz in a high fading region. The calculated results predict that with quad-path diversity, both systems could be improved by at least two orders of magnitude relative to the performance of a conventional 2-path space diversity design.

The 6 GHz example above is based on a 122 km system across the Hecate Strait in British Columbia. Field measurements from this system match the predicted outage. With quad-path diversity, there were zero frame loss events and only 15 errored seconds recorded in the worst fading month. This system has been in service with BC Tel for three years and no frame loss events have ever been recorded.

Quad-path diversity systems are most economic when configured as 1X1 systems, using two RF channels. These can be configured as single hops, multiple repeatered hops, with or without extra traffic capability. These configurations will likely be of the most interest to the owner companies.

These systems can be expanded beyond 1X1 capacity, but this would require the user to duplicate the equipment complement and spectrum used by a 1X1 system for each additional payload channel. This imposes an economic penalty that would have to be weighed carefully against other alternatives.

If a specific application demands both high performance and full-band capacity, then co-frequency cross-polarized operation may be practical if a transversal cross-polarized interference canceller is used in conjunction with the quad-path diversity configuration. Interference cancellers are a well proven technology and several systems are in service in various areas of the world. Additional detailed studies of equipment and antenna system requirements would however, be needed before Stentor routes could be designed and put into service using this technique. The current state of this technology limits application to 64 and 128 QAM modulation radios. Again, there is a economic penalty associated with the additional radio equipment required and for this reason, applications may be limited.

The mainstream application for quad-path diversity will be to provide the planner and system designer with increased performance margin. This margin can be used to achieve error-free performance on difficult paths, or to eliminate intermediate sites by designing with longer paths. Quad-path diversity provides an opportunity to re-visit radio routes that were not attempted because a workable design could not be found. It is shown in this report to be a proven solution to the problem of designing a reliable system for a long overwater reflective path.

Another possible application is the conversion of selected parts of existing radio routes to medium capacity quad-path diversity operation with greatly improved performance.

Two recommendations are made. The first is that Stentor owner companies undertake with SRCI, a review of problem radio paths to determine if the use of quad-path diversity could provide a cost effective solution. A following phase would implement that solution. The second recommendation is that SRCI under an elective radio program, develop comprehensive guidelines that will assist network planners and system designers in the owner companies to plan, design and install quad-path diversity radio systems on an ongoing basis.

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1.0 INTRODUCTION

1.1 Background

The role of digital microwave in the network is changing. For high capacity, long haul applications, fibre optic transmission, by virtue of its almost unlimited transmission capacity, will continue to be the technology of first choice. There are however, many applications where modest capacity and growth make it difficult to justify the cost of installing dual routed or ring fibre systems. Here, digital radio will continue to provide reliable wireless transport at moderate capacity, particularly in geographical areas where the cost of building a robust fibre facility is prohibitive.

There is a continuing need however, to improve the bit error performance of digital microwave radio systems during periods of atmospheric fading. The widespread use of fibre optic transmission in the network has raised the expected performance level for end-to-end data transport. End users and network planners are now less willing to make allowances for brief impairments in data transmission performance due to radio path fading events. In a competitive telecommunications market, service providers who can deliver error free performance irrespective of the time of day or month of the year will have a considerable advantage. On one hand, fibre optics has shifted the emphasis from fully built out digital radio systems that provide raw carrying capacity to medium capacity systems with fewer channels. On the other hand, radio technology wherever used, will now be expected to appear as a transparent transmission medium to the end user.

Quad-path diversity digital radio systems as described in this report, are well suited to meet this need. They can provide medium capacities and deliver near-perfect data transmission over long microwave paths under severe propagation conditions.

1.2 Purpose

The purpose of this document is as follows: First, to describe the attributes, antenna arrangements and radio equipment components for a basic quad-path diversity system. Second, to provide a method for radio system designers to calculate the expected propagation outage with quad-path diversity and to illustrate the large improvements realizable using this technique. Third, to support these findings with performance results measured on a 122 km overwater path under severe fading conditions. Fourth, to describe some alternate configurations that make quad-path

diversity suitable for a wide range of applications. Fifth, to make recommendations on how and where quad-path diversity could be used to best advantage and sixth, to identify and recommend items for future work that would be of most immediate benefit to Stentor owner companies.

2.0 DESCRIPTION

2.1 Basic Configuration

Refer to Figure 2-1, which shows a block diagram of a basic quad-path diversity system. At the transmit end of the the hop, the payload data, (DS-3's or STS-N) is applied to two transmitters operating at two different frequencies, f1 and f2. The transmitters are connected to separate antennas that are vertically spaced on the tower. At the far end, the signal from each transmit antenna is received by two vertically spaced antennas. Each receive antenna feeds a pair of receivers tuned to frequencies f1 and f2. The four received signals are IF combined in pairs, then demodulated to recover two baseband data streams which are fed to a electronic switch. This unit quickly predicts when one of the input streams is likely to become corrupted and selects the best stream, using a fast error-free switch.

It can be seen that the basic configuration of Figure 2-1 is similiar to a 1X1 frequency diversity system, equipped with IF combined space diversity on both channels, except that at each end of the hop, the protection channel transmitter is duplexed to the diversity receive antenna.

2.2 Advantages

The key advantage of quad-path diversity, is that the payload data is sent over four separate radio paths that have spatial separation at both the transmit and receive ends. An error in the output data can occur only if all four paths are simultaneously impaired.

Also from Figure 2-1, it can be seen that quad-path diversity systems will continue to provide space diversity protection with the loss of any one receive or transmit antenna. In fact these systems will continue to operate even if a transmit and a receive antenna are both out of service. This is an obvious advantage when radio routes are located in isolated areas or subject to severe wind or antenna icing conditions.

Another advantage is that two transmit and two receive antennas provide the radio system designer with four degrees of freedom to select antenna heights for the path design. This is particularly useful in the design of overwater radio paths with unblocked reflections over a large range of

refractive (K value) conditions. For example in Figure 2-1, it is usually possible to select an antenna spacing S_r at one end of the path that is optimal to combat reflections. The spacing S_t at the other end of the path can then be optimized to block reflections to/from the lower antenna and combat fading. With quad-path diversity it is possible to realize workable path designs on routes that could not otherwise be attempted.

2.3 Disadvantages

The basic system of Figure 2-1 uses two RF channels to carry the payload normally carried by one channel in a conventional space diversity system. Note however, that there is no equipment or spectrum use penalty with respect to a conventional frequency/space diversity configuration for systems that do not expand beyond 1X1. The basic system also uses baseband switching terminals at each site. Section 5 describes other quad-path diversity configurations that circumvent these limitations.

2.4 Equipment Characteristics

As stated earlier in Section 2.1, the equipment complement for a basic quad-path diversity system is very similar to that for a 1X1 frequency/space diversity system. Quad-path diversity, however, imposes a different set of performance requirements on the final baseband switch. In conventional space diversity systems, receive space diversity and IF combining are used to combat propagation impairments. The baseband switch is used primarily to protect against equipment failure and to provide a means of manually switching traffic to the protection channel during maintenance of the regular channel. For this application, speed of detection and operation are not of paramount importance. A large amount of hysteresis or time delay between the operate and release thresholds is usually designed into the switch to minimize switch activity during fading events. Because manual switching is only operated occasionally for maintenance, these switches are usually designed to be hitless, i.e. free of frame loss, on operation or release, but not necessarily errorless.

In quad-path diversity systems, the baseband switch must have characteristics that approach those of a ideal switch, i.e. zero detection and operate/release time, zero hysteresis and errorless operation and release.

The required switching speed can be illustrated as follows. During rapid fading events, the receive signal into the demodulator can degrade at rates approaching 100 dB/sec, or 10 millisecond/dB. The BER of digital radio systems degrades by approximately one decade for each dB decrease in signal-to-noise ratio. A baseband switch that initiates switching

at a BER threshold of 10^{-6} BER has 30 millisecc to detect the 10^{-6} BER condition, bring the two input streams into time alignment and complete the switch before the BER reaches 10^{-3} and loss of frame sync. If for example, DS-3 parity pulses are counted and loaded into a time-gated 8-bit overflow counter to initiate switching, the rate of arrival of parity errors for a BER of 10^{-6} will 45 pulses/sec and 176 millisecc will elapse before the counter will overflow. Clearly the baseband switch for quad-path diversity must sense a degrading demodulator input signal and initiate the switching sequence before the BER of the output data is seriously corrupted. Monitoring eye closure within the demodulator is one way of doing this.

On radio systems that employ forward error correction (FEC), counting error syndrome pulses before error correction is another method.

For quad-path diversity operation, the baseband switch must instantaneously select the better of the two input streams. This will not always be the case if, as in conventional protection switching systems, switch operation or release is based on crossing absolute thresholds. For example, if the switch thresholds were set at 10^{-8} BER, a radio channel with 10^{-7} BER would be switched off line. If the in-service channel were to subsequently degrade to 10^{-3} BER, it would not be switched out of service and replaced by the 10^{-7} BER channel, since both channels would be worse than the 10^{-8} threshold. For optimal quad-path diversity operation, the baseband switch should operate or release based on monitoring and comparing the quality of the two demodulator input signals. Thus the demodulator output with the better BER will always be selected, irrespective of the absolute BER of each input stream to the switch.

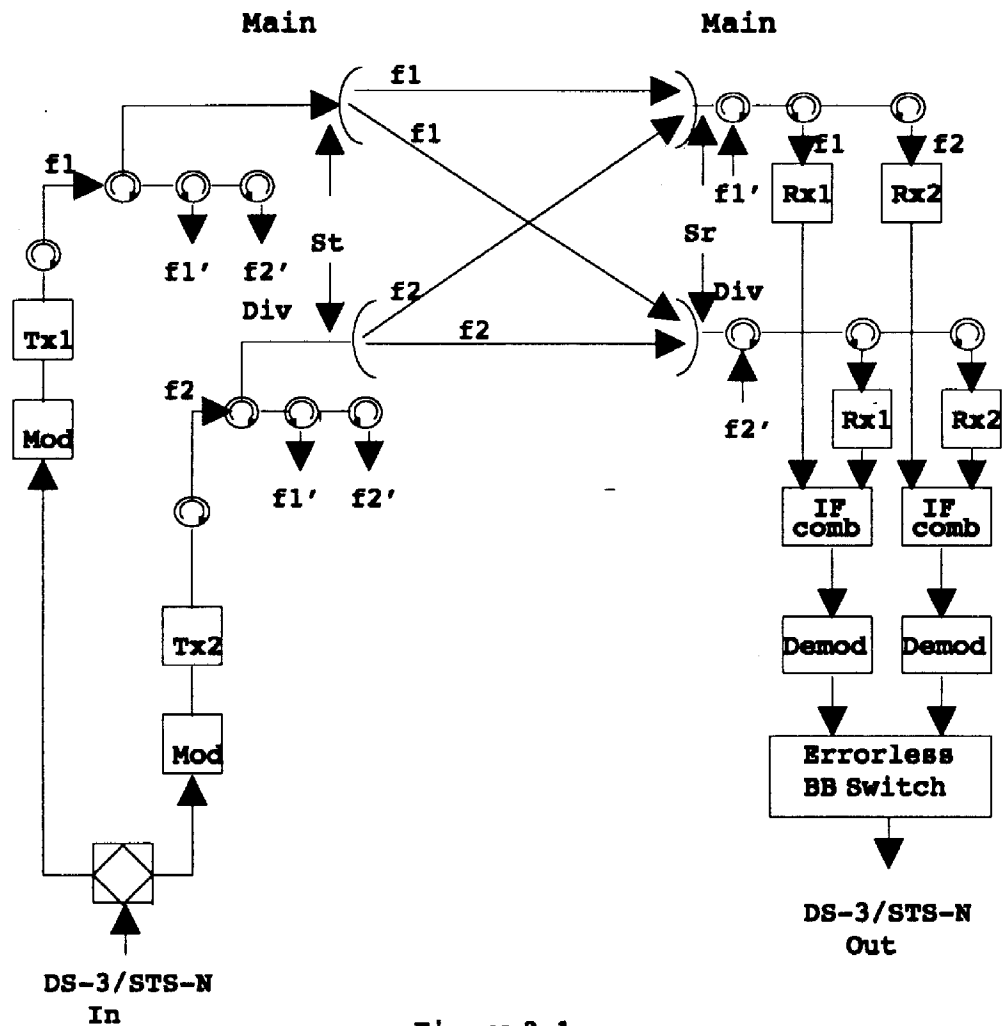


Figure 2-1
Basic Quad-Path Diversity System

3.0 AVAILABILITY OF QUAD-PATH DIVERSITY SYSTEMS

3.1 Availability Prediction

In Appendix 1, the unavailability, U_{quad} of the quad-path diversity hop is shown to be:

$$U_{\text{quad}} = [U / I_{\text{sr}}] [1 / I_{\text{st}}] \quad (\text{A1-9})$$

where:

U is the unavailability of the hop without space diversity, for the worst fading month. U can be calculated using the well-known Barnet or CCIR (Morita) fading formulas. (See Appendix 2)

I_{sr} is the Vigants space diversity improvement factor for the vertically spaced receive antennas (See Appendix 2)

$$I_{\text{sr}} = [1.2 \times 10^{-3} \times F \times S_r^2 \times 10^{\text{CFM1}/10}] / D \quad (\text{A2-4})$$

I_{st} is the space diversity improvement factor for the vertically spaced transmitter antennas.

The relationship for I_{st} will be developed below.

In equation (A2-4) F is the frequency in GHz, D is the path length in kilometers and S_r is the vertical separation in meters of the receive antennas.

CFM1 = composite flat and dispersive fade margin in dB

$$\text{CFM1} = -10 \log [10^{-\text{FFM}/10} + 10^{-\text{DFM}/10}] \quad (3-1)$$

and:

FFM is the flat fade margin, including threshold degradation due to interference.

DFM is the dispersive fade margin, calculated from the equipment signature and derated to reflect field operating conditions. A typical derating is 7 dB for paths that use the Barnet formula.

In equation (A1-9), the first bracketed term is just the unavailability of a two-path space diversity system, with a common transmit antenna, two receive antennas and spacing S_r meters. It is obtained by dividing the unavailability of the hop without space diversity U , by the Vigants space diversity improvement factor I_{sr} , which is a function of the receive antenna spacing S_r , the flat fade margin FFM and the dispersive fade margin DFM of the non-diversity hop.

Note that in equation (A1-9), the unavailability of a quad-path diversity system is further reduced by a second space diversity improvement factor I_{st} . In Appendix 1, it is shown that a quad-path diversity system can be viewed as a pair of two-path diversity systems. Each pair has a unavailability U_{sr} and the pair are spatially separated at one end by the transmit end spacing S_t . From this, the second space diversity improvement with respect to the two-pair system is, from equation (A1-8) in Appendix 1

$$I_{st} = [1.2 \times 10^{-3} \times F \times S_t^2 \times 10^{CFM2/10}] / D \quad (A1-8)$$

Where it is shown in Appendix 1 that

$$CFM2 = CFM1 + 10 \log I_{sr} \quad (A1-7)$$

The above result for CFM2 follows because applying an improvement I_{sr} is equivalent to improving the composite fade margin of the non-diversity system by $10 \log I_{sr}$. This new value CFM2 for composite fade margin is then used in equation (A2-4) and the result is (A1-8).

From equations (A1-7) and (A1-8), it can be seen that the second improvement factor I_{st} is larger than the two-path space diversity improvement factor I_{sr} . This accounts for the very high availability of quad-path diversity systems. **By spatially separating the radio paths at both ends of the hop, quad-path diversity can achieve much greater immunity from propagation outages than space diversity schemes that employ the same number of paths but separate the receive antennas only.**

Note:

Although two RF channel frequencies are used in quad-path diversity systems, no frequency diversity improvement factor is assumed. In frequency diversity systems, the two frequencies are transmitted over the same physical path. In 2-path hybrid diversity and quad-path diversity systems, these paths are spatially separated. Because of this, we do not assume that simultaneous fading on separate paths will be less likely if two different channel frequencies in the same band are used.

3.2 Sample Calculations

Appendix 2 includes the Barnett and CCIR (Morita) fading equations for predicting propagation outage. These are used with the results of preceeding Section 3.1 in two examples of very difficult path designs. These extreme cases were chosen to illustrate the availability improvement advantage with quad-path diversity.

Example 1

This is an existing 122 km overwater path in British Columbia. (BC Tel's Masset-Mt Hays system across the Hecate Strait). The outage calculation details are shown in Appendix 3. The results are summarized as follows:

Outage Time, Intertoll Objective, 1 Way For Worst Fading Month (wfm)	9.7	sec
---	------------	------------

Calculated Outage, 1-Way, Non-Diversity (sec/wfm)	2234	sec
--	-------------	------------

Rcv Diversity Improvement , $S_r = 13$ meters	6.92	
---	------	--

Calculated Outage, 1-Way, 2-Path Space Diversity, (wfm)	323	sec
--	------------	------------

Trmt Diversity Improvement, $S_t = 32$ meters	290	
---	-----	--

Outage, 1-Way, Quad-Path Diversity (wfm)	1.1	sec
---	------------	------------

The 2-path receive space diversity design misses the outage objective by a factor of 23. With quad-path diversity the predicted outage is 9 times better than the objective.

Example 2

This is non-specific, hypothetical 4 GHz, 70 km path over land and subject to Barnett C = 2 fading conditions. Outage calculation details are shown in Appendix 4. The 34 dB Flat Fade Margin assumed is consistent with a radio system gain of 100 dB, with 100 meters of WC 281 waveguide and horn antennas at each end of the path. Diversity antenna spacing is 10 meters at each end.

The results are summarized below.

Outage Time, Intertoll Objective, 1 Way For Worst Fading Month (wfm)	5.6	sec
---	------------	------------

Calculated Outage, 1-Way, Non-Diversity (wfm)	2399	sec
--	-------------	------------

Rcv Diversity Improvement , $S_r = 10$ meters	12.2	
---	------	--

Calculated Outage, 1-Way, 2-Path Space Diversity, (wfm)	197	sec
--	------------	------------

Trmt Diversity Improvement, $S_t = 10$ meters 147

Calculated Outage, 1.4 sec
1-Way, Quad-Path Diversity

The 2-path receive space diversity design misses the outage objective by a factor of 37. With quad-path diversity, the result outage is less than the objective by a factor 4.

4.0 FIELD RESULTS

4.1 Masset-Mt Hays System

Refer to Figure 4-1. This is the 6 GHz system described in Example 1 of Section 3.2. Mt Hays is located above the city of Prince Rupert, B.C. Masset is 122 km across the Hecate Strait in the Queen Charlotte Islands Group. Some path geometries are exposed to unblocked sea reflections for K values from 0.6 to 3.2. The hop also experiences long periods of upfading and severe flat and dispersive fading. Upfades of up to 18 dB on the path between the topmost antennas and continuous severe fading for thirty-six hours on all four paths have been recorded during the monitoring period.

The equipment used on Masset-Mt Hays is a 6 GHz 90 Mbs radio system carrying 2 DS-3 streams in 30 MHz using 16 QAM modulation. The radio is equipped with IF slope equalizers and IF transversal (adaptive time domain) equalizers. The dispersive fade margin calculated from the equipment signature is 48.5 dB. The IF combiners used in the quad-path diversity setup track and phase equalize differential phase changes up to 35,000 degrees/sec. Each IF combiner feeds an errorless baseband switch unit. Switch initiation for fading impairments is based on differential detection. of eye closure within the two demodulators that feed the errorless switch.

Table 4-1 below summarizes the measured transmission results for June, July and August of 1989. At that time, Masset-Mt Hays was configured as a hybrid diversity system, as shown in Figure 4-1. A single antenna was installed at Mt Hays at 43 meters above ground level (AGL) and two antennas at Masset at 91 meters and 75 meters AGL. The objective here was to determine the performance using the maximum diversity spacing that could still meet path clearance criteria. The impaired data, particularly for the non-diversity channel indicates that this is indeed an active path. The results in Table 4-1 show that even with space diversity, the 29 sec/yr one-way intertoll objective is missed by an order of magnitude. At best, two-path diversity can achieve only short-haul performance on this route.

Early in September, 1989, the bottom antenna at Mt Hays in Figure 4-1 was moved to a new position 6.5 meters below the top antenna. With this spacing, fading due to sea reflections does not occur simultaneously on both paths. Table 4-2 shows the measured results for Sept 10-Oct 4/1989 (24 days). These results indicated that the 29 sec/yr one-way intertoll objective would still be exceeded by at least a factor of six. From this it was concluded that a two-path diversity design would be unable to cope with sea reflections and fading anomalies that occur concurrently on this route. Additional diversity radio paths were needed and quad-path diversity was the proposed solution.

Early in 1990, space diversity receivers and IF combiners were installed at both sites and a second antenna was added at Mt Hays to convert the 1X1 hybrid diversity setup of Figure 4-1 to the quad-path diversity configuration of Figure 4-2. The 13 meter antenna spacing at Mt Hays was selected to ensure that the signal transmitted from the top antenna at Masset would not be exposed to simultaneous reflection nulls at both receive antennas at Mt Hays. The 60 meter height for the lower antenna at Masset was selected to bury it with respect to sea reflections of the Mt Hays signals.

The data for one of the two-path space diversity streams feeding the errorless switch was obtained by monitoring the data stream transmitted from the lower Masset antenna and IF combined at Mt Hays. This is shown in the columns labelled as S.Div in Table 4-3. This signal is not subject to reflection impairments. The expected yearly outage based on three times the measured worst month outage is 567 seconds for a 10^{-6} BER criteria for outage. Again this misses the intertoll objective by more than an order of magnitude.

This re-affirmed our earlier conclusion, that whether the lower antenna is placed to eliminate simultaneous reflection nulls, or buried with respect to sea reflections, a two-path design would not meet intertoll outage objectives on this route.

In Section 3.2, Example 1, the calculated outage time for a 10^{-6} BER, with the two-path diversity setup was 323 seconds for the worst fading month. The measured results for July, 1990 from Table 4-3 are in reasonable agreement, with 189 seconds where the BER exceeded 10^{-6} and 103 frame loss seconds.

The calculated quad-path diversity outage time in Section 3.2 for a 10^{-6} BER was 1.1 seconds. The measured outage was zero seconds and no frame loss events. The quad path diversity data had only 15 errored seconds. As Table 4-3 indicates, these occurred as a result of 52 DS-3 bit errors. These bit errors were distributed over the 15 errored seconds as single bit errors and error bursts of at most 14 errors in any one second interval. This system has been in service for three years. No frame losses have ever been recorded.

The errorless baseband switch used in the Masset-Mt Hays system is specified to detect, time delay equalize and switch a channel with a stationary 10^{-6} BER in 40 millisecond and a channel with a stationary 10^{-3} BER in 200 microseconds. This means that at 10^{-6} BER, just less than 2 bit errors on average could slip through before switchover to an unimpaired data stream. At 10^{-3} BER, just less than 9 bit errors on average, could slip through. The results above are consistent with this. The bit errors observed in the quad-path diversity setup are likely the result of the finite response time of the errorless switch, rather than insufficient diversity paths. The results for the number of seconds for which BER exceeds 10^{-6} , 10^{-4} , or loss of frame occurs are all zero.

This indicates, that even under severe fading and upfading conditions, there were no instances where all four paths were seriously impaired. The equipment at the receive end must merely find an unimpaired path and select it quickly enough. Therefore, quad-path diversity, when suitably implemented is a powerful countermeasure against fading.

It should be noted that current generation digital radios equipped with forward error correction (FEC) are capable of detecting, delay equalizing and switching a radio channel with 10^{-6} BER in less than 15 milliseconds. Improved errored seconds performance should result if newer generation equipment is configured for quad-path diversity operation.

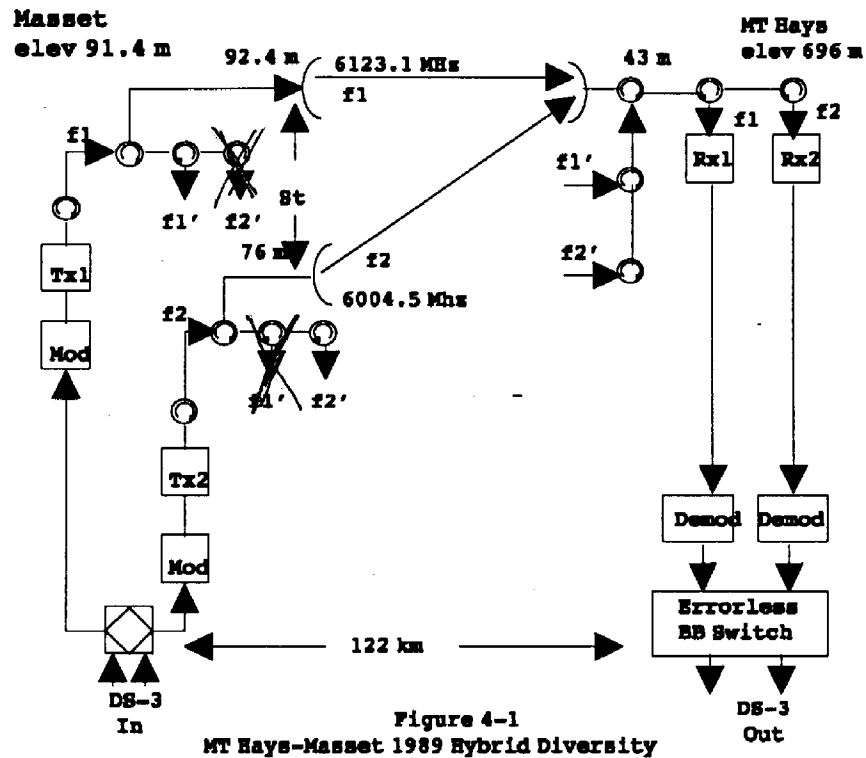


Figure 4-1
MT Hays-Masset 1989 Hybrid Diversity

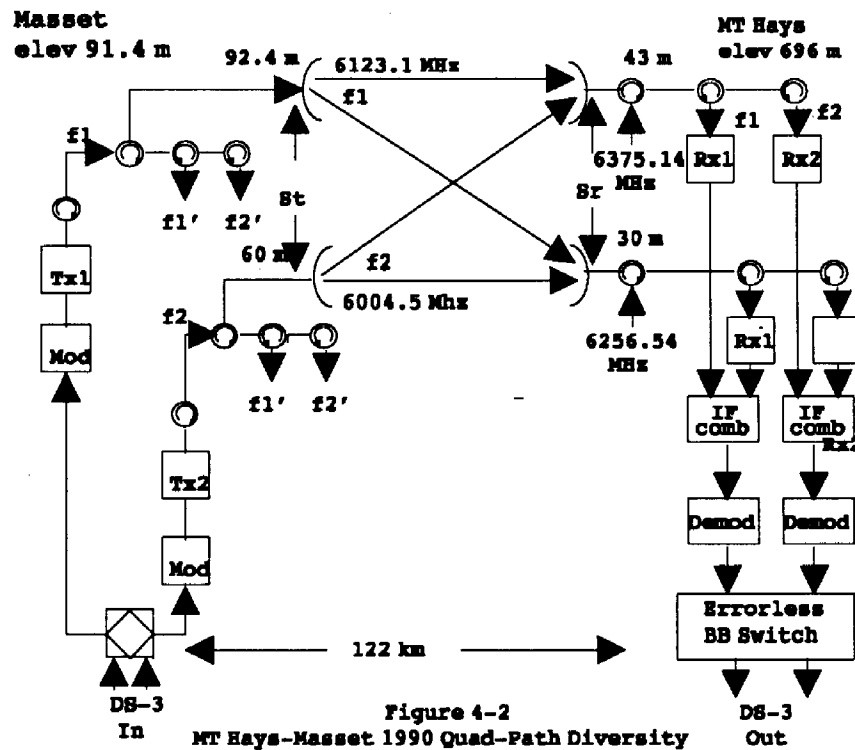


Figure 4-2
MT Hays-Masset 1990 Quad-Path Diversity

Table 4-1
2-Path Diversity Results for Jun-Aug 1989
Rcv Antennas Spaced for Max Diversity Spacing

Event	June/1989		July/1989		Aug/1989	
	Non-Div	Space Div	Non-Div	Space Div	Non-Div	Space Div
Error Seconds	1399	180	incpl	65	14835	195
BER Exceed 10-6	1165	98	incpl	14	14798	167
BER Exceed 10-4	1118	97	incpl	14	14780	166
Fr Loss Sec	1118	75	incpl	14	14779	166
Fr Loss Events	518	32	incpl	10	1005	71

incpl - incomplete data

Table 4-2
2-Path Diversity Results for Sept 1989
Rcv Antennas Spaced for No Common Reflective Fades

Event	Sept10-Oct4	
	Non-Div	Space Div
Error Seconds	incpl	141
BER Exceed 10-6	incpl	57
BER Exceed 10-4	incpl	44
Fr Loss Sec	incpl	25
Fr Loss Events	incpl	16

incpl - incomplete data

Table 4-3
1990 Results
Quad-Path Diversity Performance

Event	July/1990		Aug/1990		Sept1990	
	S.Div	Q.Div	S.Div	Q.Div	S.Div	Q.Div
Bit Errors		52		34		1
Max Bit Err/sec		14		10		1
Min Bit Err/sec		1		1		1
Error Seconds	240	15	116	15	7	1
BER Exceed 10-6	189	0	69	0	7	0
BER Exceed 10-4	159	0	64	0	3	0
Fr Loss Sec	103	0	59	0	3	0
Fr Loss Events	65	0	22	0	2	0

5.0 OTHER CONFIGURATIONS

5.1 Protection Channel Access

In the basic configuration of Figure 2-1, the two input data streams are permanently bridged together to feed two RF channels. Figure 5-1 shows an alternate configuration, where access switches are added to the baseband of one RF channel. This configuration closely resembles a 1XN frequency diversity /space diversity system, equipped for 1X1 and access switching. If the switching system is fast enough, quad-path diversity performance is not compromised when the

RF channel that is off-line is used to carry extra traffic. The switching system must sense degradation of the traffic channel at the receive end, send a bridge order to the transmit end, time delay equalize the two data paths and complete the errorless switch well within the 30 millisecond time window between a 10^{-6} BER and loss of framing. Current radio protection systems that count error syndrome pulses from forward error correction circuits in the radio can perform this operation in about 15 milliseconds.

Extra traffic operation with quad-path diversity is feasible. The key is fast detection and operation of the errorless switch.

5.2 Multi-Hop Quad-Path Diversity

Figure 5.2 shows a multi-hop quad-path diversity configuration. Here, at each repeater site, the output from each IF combiner is regenerated and then re-transmitted from separate vertically spaced antennas. At the end terminal of the switching section, the baseband signals are applied to the errorless switch. This scheme can be used with or without the extra traffic feature described in Section 5.1 above. An outage occurs if:

- a) All four radio paths on one or more hops are impaired, or
- b) Both signals transmitted from the top antenna of one or more hops are corrupted, while at the same time both signals from the bottom antenna of one or more hops are corrupted.

The unavailability of such a N-hop quad-path diversity system can be determined by considering that:

If U_{quad} = quad-path unavailability for the worst hop and

U_s = 2-path space diversity unavailability for the worst hop

and terms involving $(U_{\text{quad}})^2$ and $(U_{\text{quad}})(U_s)$ are ignored then

U_N , the quad-path unavailability for N hops can readily be shown to be:

$$U_N < N (U_{\text{quad}}) + N(N-1) (U_s)^2 \quad (5-1)$$

In fact for practical values of $N = 5-7$ hops,

$$U_N < N \cdot (U_{\text{quad}}) \quad (5-2)$$

The results of Section 3 predict that quad-path diversity can provide more than two orders of magnitude improvement over 2-path space diversity. The field results in Section 4 confirm this for improvements in 10^{-6} BER seconds and frame

loss seconds performance (where the minor bit error effects of non -zero switching time are not noticable)
The radio paths in Section 3 are extreme examples. Even so, Equation 5-2 above indicates that a multi-hop quad -path diversity system consisting of $N = 4$ hops, each hop as severe as the 4 GHz system of example 2 in Section 3, would have only 5.6 sec outage in the worst fading month. This is still within the intertoll objective for a a single hop.

Multi-hop quad path diversity is feasible. Again the key is fast detection, zero hysteresis and errorless switch operation

5.3 Frequency Re-Use

The basic system described in Section 2.1 and the enhanced systems of Section 5.1 and 5.2 above do not require more radio equipment, antennas, or spectrum than a two-path 1X1 frequency/space diversity configuration. However, to double the capacity, the original 1X1 equipment would have to be duplicated, and connected to the same antennas. Two additional radio channels would normally be required. This reduces the ultimate capacity of the band.

Figure 5-3 shows a scheme that uses co-frequency cross-polarized operation with electronic cross-polarization interference cancellers (XPIC) to double the capacity. This restores the band capacity that would normally be compromised by using the quad-path diversity setup over the full band. In fact the capacity relative to a 1XN system is improved, as the spectrum normally reserved for the protection channel in a 1XN system is now used to carry traffic. For example, in the 6 GHz band, a 1XN system provides 7 traffic carrying channels, with one protection channel that can be used for restoration. A cross-polarized quad-path diversity system would provide 8 traffic carrying channels with 8 channels available for restoration use. (In the restoration mode the traffic channels operate with 2-path space diversity protection). In the 8 GHz band, a full-band quad-path diversity system would provide 6 traffic carrying channels with 6 channels available for restoration.

Further investigation of antenna system and equipment requirements would be necessary before a working system using this technique could be put into service in the Stentor network. Two factors however, make co-frequency cross-polarized operation an alternative to consider if an application demands both high performance and full-band, full capacity operation.

The first factor is the availability of transversal cross-polarization interference cancellers (XPIC). These can reduce degradation of cross-polarization discrimination

(XPD) during fading, by 20 dB. Thus co-frequency cross-polarized systems equipped with XPIC are more likely to meet intertoll performance requirements than systems that are not so equipped. XPIC technology is now well proven and several systems are in service throughout the world. At this time however, the technology is limited to 64 and 128 QAM modulation radios.

The second factor is the use of quad-path diversity, which is the subject of this report. As shown in Section 3, these systems require less fade margin than 2-path space diversity systems to deliver a given level of performance. Because XPD degradation increases with fade depth, quad-path diversity systems will be more immune to this impairment than 2-path space diversity systems.

Co-channel cross-polarized quad-path diversity operation using interference cancellers is an alternative that merits consideration in those cases where both full band capacity and high performance are needed. An economic trade-off must be made to achieve these benefits, as double the amount of radio equipment is required relative to conventional 1XN frequency/space diversity systems. Further evaluation of antenna system and equipment requirements would have to be undertaken by SRCI to determine feasibility for a specific application.

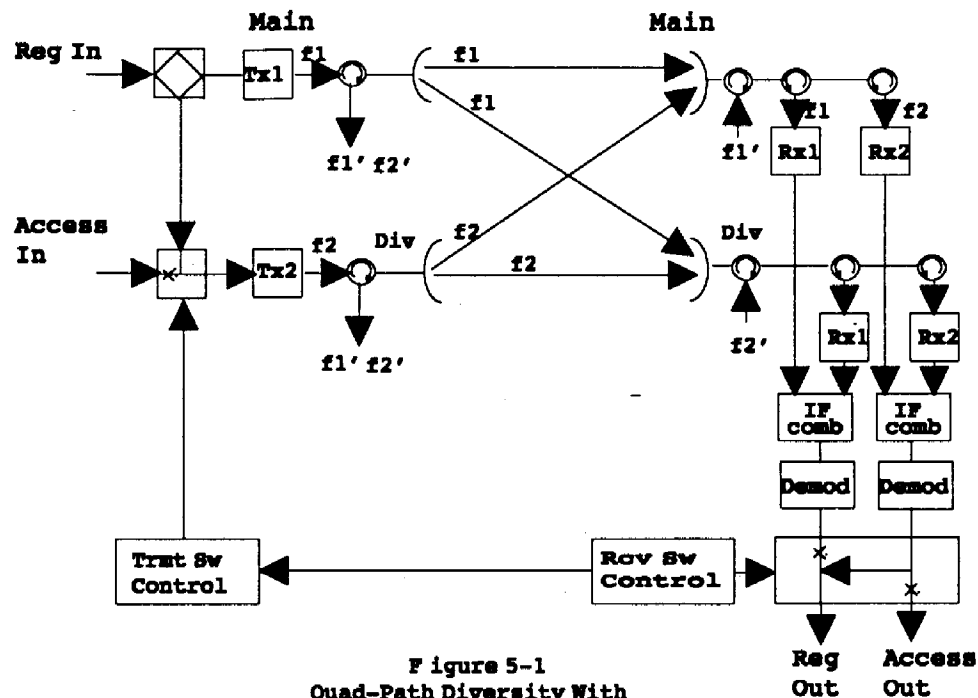


Figure 5-1
Quad-Path Diversity With
Protection Channel Access

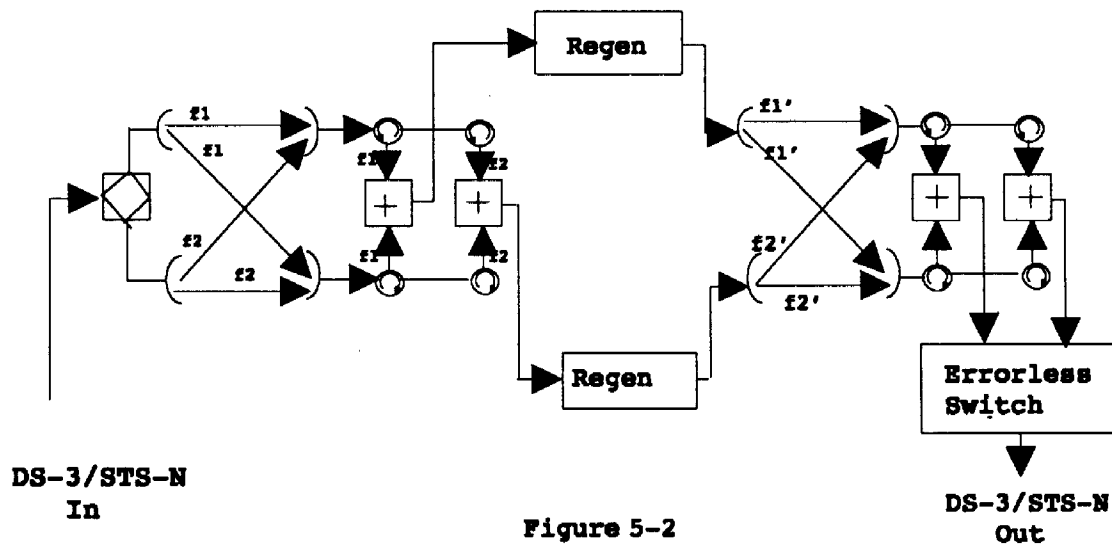


Figure 5-2
Multi-Hop
Quad-Path Diversity

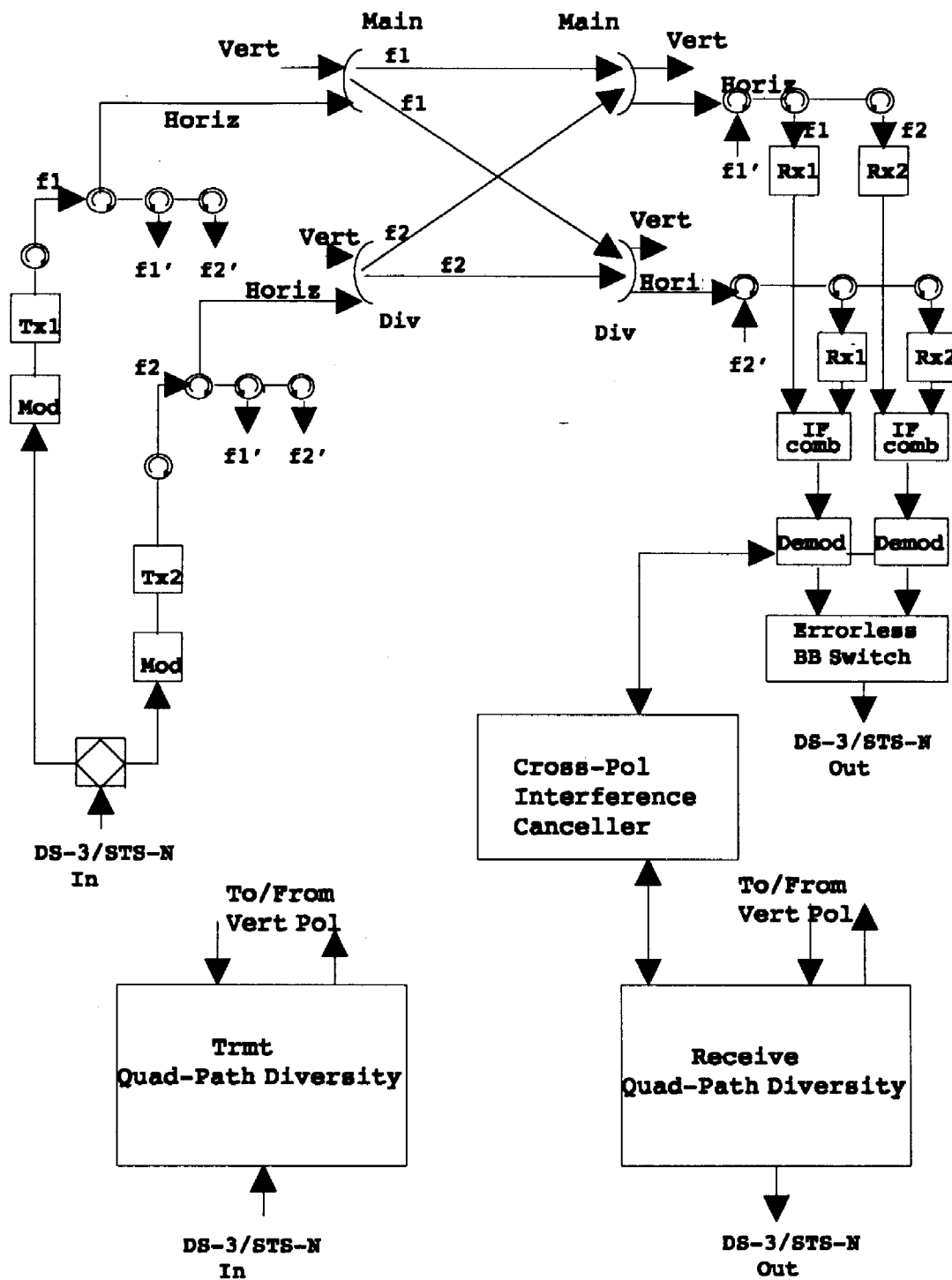


Figure 5-3
C0-Frequency Cross-Polarized Operation

6.0 APPLICATIONS

6.1 Performance Improvement

Quad-path diversity systems can provide two orders of magnitude improvement in availability over conventional two-path space diversity systems. The network planner and system designer can make use of this extra performance margin in several ways:

- The performance of routes that exhibit poor data performance due to fading can be improved.
- In some geographical areas, quad-path diversity may provide a secure and more economic alternative to building a dual routed fibre system.
- Path designs that could not be attempted in the past may now be possible. In this category are very long paths, overwater paths and reflective paths. In some cases longer paths may permit the decommissioning of intermediate repeater sites.
- The very high immunity of quad-path diversity systems to antenna damage can be used to improve the reliability of radio paths that are located in areas where icing and windstorms are a risk.

6.2 1X1 Systems

For routes where the capacity requirements are not expected to grow beyond that of a single protected RF channel, and which already require a 2-path space diversity design, there is little reason not to use quad-path diversity, if spectrum availability permits. The amount of equipment required and occupied spectrum is the same as for a 1X1 frequency/space diversity system. The advantages of improved data performance and increased antenna structure reliability are strong incentives.

6.3 (1X1)XN Systems and Co-Frequency Cross-Polarized Systems

To expand a quad-path diversity system, the initial 1X1 configuration (except for antennas) must be duplicated. For this reason, applications will be more limited than 1X1 applications. A possible exception is long overwater crossings which connect population centers, but where the cost of a secure submarine fibre facility is prohibitive.

6.4 Existing Routes

Quad-path diversity can be most economically implemented using existing sites and in frequency bands where suitable antenna structures are already in place. A review of existing routes by owner companies and SRCI to determine those for which net benefits could be gained by the use of

quad-path diversity would be worthwhile. Two possible application areas are identified below.

6.4.1 Technology/Route Diversity for Network Surveillance and Control

The architecture of the Stentor long haul high capacity network is moving rapidly toward three very high capacity SONET fibre routes, with numerous cross-connects, cross-links, multiplexers, switches and other critical network elements. The number of data channels required to monitor and control critical elements and the bandwidth required for these channels continues to escalate. Although the SONET format allows for much of this information to be carried within the SONET overhead, there may be great operational benefits to having critical OAM&P functions transported on a separate facility to make these immune to failure modes that result in loss of SONET overhead. A medium capacity quad-path diversity radio system is well suited to provide this facility.

6.4.2 Critical Services

Quad-path diversity radio systems are capable of delivering availability performance 100 times better than radio systems that employ 2-path space diversity. As a result they can match the BER performance of fibre systems (for moderate capacities) even in the presence of fading. At the same time they retain the inherent advantages of radio systems over cabled transmission, - much greater security against interruptions due to cable cuts, sabotage, vandalism or natural disasters and no errors when protection switches are operated during routine maintenance. A business opportunity may exist to serve critical applications that need this degree of transmission reliability.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1

Quad-path diversity can provide two orders of magnitude improvement in availability over conventional two-path diversity configurations. As a result, quad-path diversity radio systems can match the data integrity performance of fibre optic transmission systems, even during periods of severe multipath fading.

7.2

The mainstream applications will likely be improvement of existing and planned routes.

7.3

Quad-path diversity can be most economically implemented as a 1X1 configuration, where the equipment complement and the spectrum required is similar to a 1X1 frequency/space diversity system. These systems can be configured to include extra traffic capability and multi-hop systems with regenerative repeaters. We believe that these will be the configurations that will be of interest to most owner companies.

7.4**Recommendation:**

Quad-path diversity can provide a workable path design for very difficult radio paths. It is recommended therefore, that Stentor owner companies undertake a review of problem radio hops with SRCI assistance to determine whether a quad-path diversity radio system could provide a cost effective solution. SRCI can provide technical assistance under an owner-specific program as follows:

- Assist in path analysis and design of a quad-path diversity alternative for a specific application.
- Perform an analysis of the antenna system requirements and assist in the design of the antenna system.
- Assist in the selection of system configuration and equipment.
- Assist in the evaluation of performance and work with the equipment supplier to identify required performance improvements and supply modifications as necessary.

7.5

Recommendation:

It is recommended that SRCI establish, with owner companies, an elective radio program to prepare and issue guideline documents that will allow network planners and designers to plan, cost, design and build quad-path diversity radio systems on an ongoing basis. The statement of work may differ with frequency band, route, modulation scheme and antenna structure type, so this should be a subject for further discussion. Suggested items are as follows:

- Radio equipment requirements for quad-path diversity
- Antenna system requirements and limitations
- Planning guidelines for future growth
- Availability calculation guidelines
- Recommended equipment platforms with ordering and optioning guidelines
- Installation , line up and acceptance guidelines

APPENDIX 1 Quad-Path Diversity Unavailability

Refer to Figure A1-1a. This is a 2-path diversity system. The two paths A and B extend from a single transmit antenna to two vertically spaced receive antennas with spacing S_r meters. The joint unavailability is given by

$$U_{sr} = P[A \text{ B}] = P[A] P[B/A] \text{ where} \quad (A1-1)$$

$P[A] = U$, the unavailability of path A.

$P[B/A]$ = the unavailability of path B, given that path A is unavailable.

It can be recognized that the conditional probability $P[B/A]$ is just the reciprocal of the Vigants space diversity improvement factor for a receive antenna spacing S_r (Appendix 2, Equation A2-4). Therefore

$$U_{sr} = [U] [1/I_{sr}] \quad (A1-2)$$

Now refer to Figure A1-1b. The joint probability that all four paths are unavailable is given by

$$U_{quad} = P[ABCD] = P[AB] P[CD/AB] \quad (A1-3)$$

where

$P[AB] = U_{sr}$ is the unavailability of a 2-path diversity system with paths A and B and receive antenna spacing S_r .

$P[CD/AB]$ is the unavailability of a second 2-path diversity system with paths C and D and the same receive antenna spacing S_r , given that the first 2-path system (with paths A and B) is unavailable.

For simplicity, we assume that the two-path unavailabilities are the same, i.e.

$$P[AB] = P[CD] = U_{sr} \quad (A1-4)$$

The path pair AB and CD in Figure A1-1b can each be replaced by an equivalent non-diversity path with the same unavailability U_{sr} as shown in Figure A1-1c.

To show this we can define a space diversity improvement function I as:

I = the Vigants improvement formula for antenna spacing $S > \text{some value } s$. (Appendix 2)

$$= [1.2 \times 10^{-3} \times F \times S_t^2 \times 10^{[CFM/10]}] / D$$

$$= 1 \text{ for } S < s$$

The worst month outage is determined by dividing the Barnet or CCIR fading equation by I , so the unavailability of a non-diversity or a space diversity system can be described by the same function of the composite fade margin CFM. i.e. a non-diversity system is taken as a special case of a space diversity system where $S < s$ and the improvement is one.

$P[A]$, $P[B]$, $P[AB]$ and $P[CD]$ can then all be expressed by the same function of the composite fade margin CFM of the form

$$P[\quad] = KQ \times F^b \times D^c \times 10^{-[CFM]/10} \quad (A1-6)$$

(See Ref (2) in Appendix 2)

where $CFM = CFM1 + 10 \log I$

CFM1 is the composite fade margin of a non-diversity path A or B.

and KQ , b and c take on appropriate values for the Barnet and the CCIR formulas. Thus a space diversity system can be modelled by Equation (A1-6) as a equivalent non-diversity system with an enhanced composite fade margin. (Note 1)

Also, since the conditional probability $P[B/A]$ is given by the reciprocal of the Vigants formula for space diversity improvement, with the composite fade margin CFM1 for path A or B is used in the square brackets in Equation (A1-5), it follows that the conditional probability $P[CD/AB]$ will also be given by the same formula for I . The composite fade margin used to in the square brackets of Equation (A1-5) however, will be that corresponding to the equivalent non-diversity system. This is

$$CFM = CFM2 = CFM1 + 10 \log I_{sr} \quad (A1-7)$$

The space diversity systems consisting of paths A,B and C,D in Figure A1-1b can thus be modelled as equivalent non-diversity paths as in Figure A1-1c. These two equivalent paths are separated at the transmit end by a vertical spacing S_t meters.

$P[CD/AB]$ in (A1-3) can be viewed as the reciprocal of a second Vigants space diversity improvement factor I_{st} . This factor is a function of the the transmit antenna spacing S_t and the composite fade margin of either of the equivalent single paths in Figure A1-1c. This is the composite fade margin CFM2 of a single path that would result in the same unavailability as the 2-path diversity system of paths AB or CD. This is

$$CFM2 = CFM1 + 10 \log I_{sr} \quad (A1-7)$$

This value CFM2 for the composite fade margin is then used in the Vigants space diversity improvement formula (equation (A2-4) in Appendix 2) to obtain

$$I_{st} = [1.2 \times 10^{-3} \times F \times S_t^2 \times 10^{CFM2/10}] / D \quad (A1-8)$$

This improvement factor is applied to the pair of equivalent paths AB and CD each with unavailability U_{sr} to obtain the quad-path diversity U_{quad} as follows: (Note 2)

$$U_{quad} = [U_{sr}][1/I_{st}] = [U][1/I_{sr}][1/I_{st}] \quad (A1-9)$$

Note 1

From another perspective, consider an observer located at the receive end of the 2-path system of Figure A1-1b, who first measures the unavailability U of the single path A or B, then the unavailability of the combined signals from paths A and B during the worst fading month. Further, assume that he cannot see the antenna system and cannot ascertain whether the signal that feeds his demodulator for the second measurement comes from a single receiver or space diversity equipped receiver system.

If he is told that he is monitoring a space diversity system, he would assume that he is measuring the combined output from two paths, each path having some composite fade margin CFM1 dB, and unavailability U , which has been improved by a space diversity improvement factor I_{sr} .

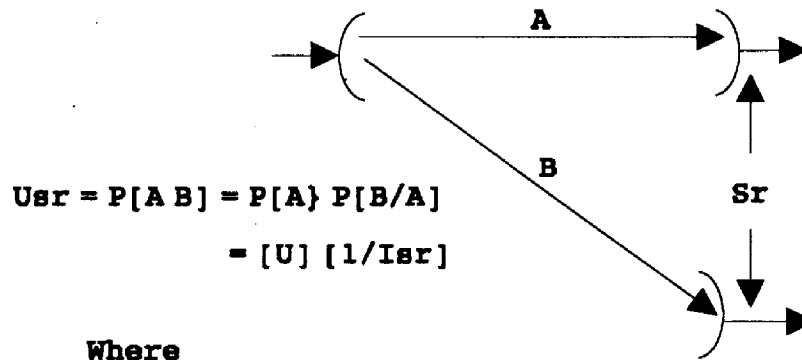
If however, he is told that he is looking at a non-diversity system, he would conclude that the single path has improved and the path now has a higher composite fade margin. If asked to determine what that composite fade margin was, he would take the measured unavailability, work backwards from the Barnett or CCIR fading formulas of Appendix 2 and calculate a value CFM2, that was $10 \log I_{sr}$ higher than that for CFM1.i.e.

$$CFM2 = CFM1 + 10 \log I_{sr} \quad (A1-7)$$

Similiarly, in Figure A1-1b, the 2-path space diversity system consisting of paths C and D can be replaced by an equivalent non-diversity hop with the same unavailability U_{sr} and composite fade margin CFM2.

Note 2

Again from another perspective, consider an observer at the receive end of the path in Figure A1-1c, who is looking at the inputs to the two demodulators. They appear to be from the two equivalent non-diversity paths with improved composite fade margin CFM2 as given in Equation (A1-7) above. These two paths are spatially separated at the transmit end by S_t meters as in Figure A1-1c. This can be modelled as a hybrid diversity setup with baseband receive end switching and transmit antenna spacing of S_t meters. Applying the Vigants space diversity improvement factor, the result is, equation (A1-8) and (A1-9).



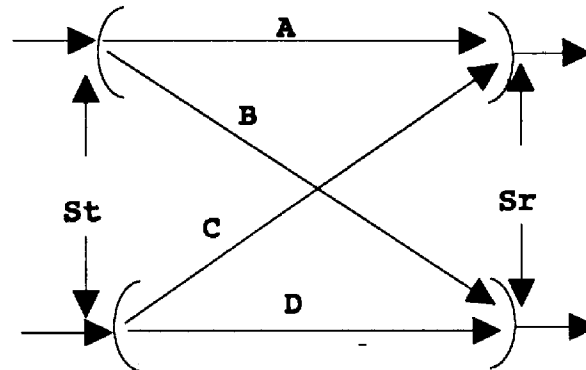
$$\begin{aligned} U_{sr} &= P[AB] = P[A] P[B/A] \\ &= [U] [1/I_{sr}] \end{aligned}$$

Where

$U = P[A]$ = unavail of path A (or path B)

I_{sr} = Vigants Space Div Improvement Factor

Figure A1-1a
2-Path Diversity Unavailability



$$\begin{aligned} U_{quad} &= P[ABCD] = P[AB] P[CD/AB] \\ &= [U_{sr}] P[CD/AB] = [U_{sr}] [1/I_{st}] \end{aligned}$$

Where

I_{st} is a Vigant's space div improvement factor for a pair of space div systems AB and CD separated at the transmit end by S_t meters.

Figure A1-1b
Quad-Path Diversity Unavailability

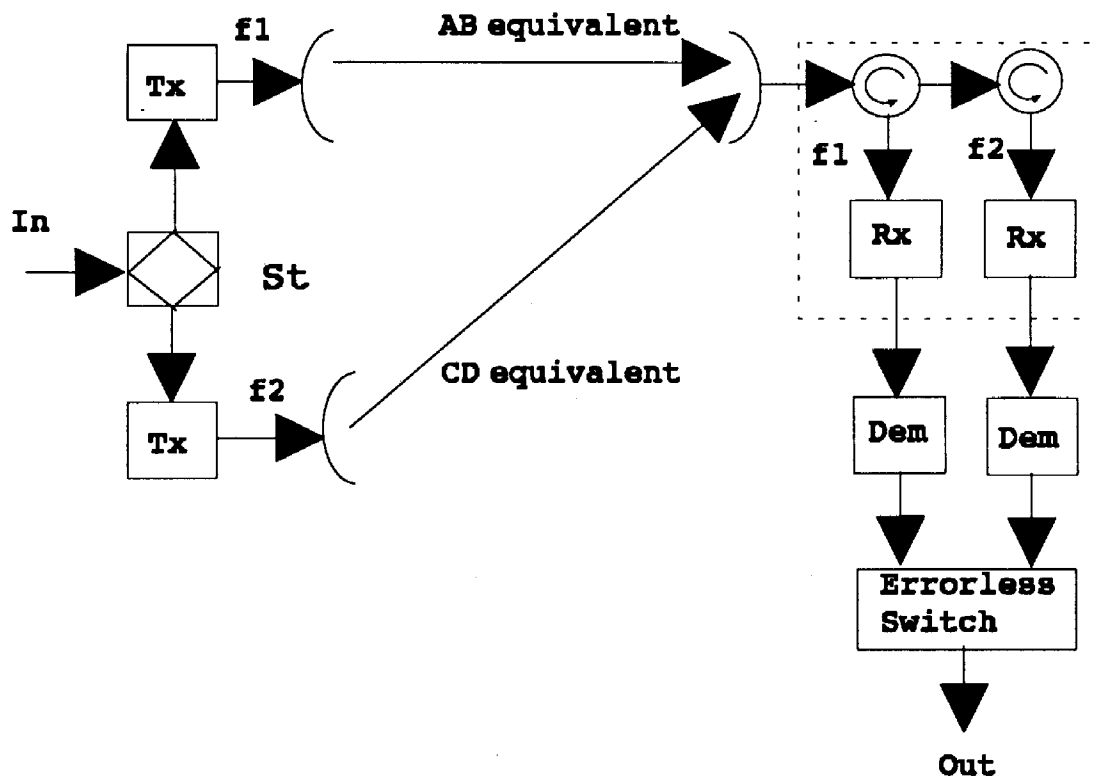


Figure A1-1c
2-Path Representation of Quad-Path Diversity

APPENDIX 2 Path Fading Formulas

Two fading formulas are commonly used to as a basis to predict the worst fading month unavailability U, due to microwave radio radio path fading.

Using the Barner fading equation⁽¹⁾, U is (in metric form):

$$U = 6.0 \times 10^{-7} \times C \times F \times D^3 \times 10^{-CFM/10} \quad (A2-1)$$

Where:

F = freq in GHz

D = path length in km

$$C = [X][w/15.2]^{-1.3}$$

X = 2, 1, or 0.5 for (A2-2)
humid, average or
dry climates
respectively.

and w is the rms variance of the elevation along the path.

CFM is the composite fade margin

In mountain or coastal regions, the CCIR (Morita) fading equation⁽²⁾ is often used, as follows:

$$U = KQ \times (F)^{1.2} \times D^{3.5} \times 10^{-CFM/10} \quad A2-3)$$

Where:

$$KQ = 0.39 \times 10^{-9} \quad \text{dry mountainous regions}$$

$$1.0 \times 10^{-9} \quad \text{Inland climate with average rolling terrain}$$

$$9.9 \times 10^{-8} / [(h_1 + h_2)]^{1/2} \quad \text{coastal and overwater regions}$$

h₁ and h₂ are the antenna heights above sea level.

Space Diversity Improvement Factor

This is the well known empirical formula developed by Vigants (1) and is given in metric form by

$$I_{sr} = [1.2 \times 10^{-3} \times F \times (S_r)^2 \times 10^{CFM/10}] / D \quad (A2-4)$$

where

F is the RF channel frequency in GHz

S_r is the receive antenna spacing in meters

D is the path length in km

CFM is the composite fade margin in dB

(1) A. Vigants, "Space Diversity Engineering", BSTJ, March, 1975, Vol 54, No. 1, pp 103-142.

(2) Report 338-6, Annex II, page 392, Reports of the CCIR, XVII th Plenary Assembly, Dusseldorf, 1990.

APPENDIX 3 MASSET-MT HAYS PATH OUTAGE CALCULATION

This describes the outage calculations for a existing 122 km overwater path in British Columbia. (BC Tel's Masset-Mt Hays system across the Hecate Strait).

Frequency	6 GHz
Path Length	122 km
Fading Model	Morita h1 = 151 m h2 = 726 m
Fading Season	3 months
Flat Fade Margin (10^{-6} BER)	34 dB
Disp Fade Margin (From Eqpt Signature, 10^{-6} BER)	48.5 dB
Disp Fade Margin Derating, $5 + 10 \log (122/42)^3$ *Practice in BC Tel for long overwater paths is to derate by 5 dB plus cube law with distance above 42 km (26 miles).	18.9 dB*
Derated Dispersive Fade Margin	29.6 dB
Composite Fade Margin, CFM1 (10^{-6} BER)	28.3 dB
Outage Time, Intertoll Objective, 1 Way For Worst Fading Month (wfm)	9.7 sec
Outage, 1-Way, Non-Diversity sec/wfm	2234
Rcv Diversity Improvement , $S_r = 13$ meters	6.92
Outage, 1-Way, 2-Path Space Diversity, (wfm)	323 sec
Trmt Diversity Improvement, $S_t = 32$ meters	290
Outage, 1-Way, Quad-Path Diversity (wfm)	1.1 sec

The 2-path receive space diversity design misses the outage objective by a factor of 23. With quad-path diversity the predicted outage is 9 times better than the objective.

APPENDIX 4 HYPOTHETICAL 4 GHz PATH OUTAGE CALCULATION

This is hypothetical, 4 GHz, 70 km path over land and subject to Barnet C = 2 fading conditions. The 34 dB Flat Fade Margin assumed below is consistent with a radio system gain of 100 dB, with 100 meters of WC 281 waveguide and horn antennas at each end of the path. Diversity antenna spacing is 10 meters at each end.

Frequency	4 GHz
Path Length	70 km
Fading Model	Barnet C = 2
Fading Season	3 Months
Flat Fade Margin, (10^{-6} BER)	34 dB
Disp Fade Margin (From Signature, 10^{-6} BER)	45 dB
Disp Fade Margin Derating,	7 dB
Derated Dispersive Fade Margin	38 dB
Composite Fade Margin, CFM1 (10^{-6} BER)	32.5 dB
Outage Time, Intertoll Objective, 1 Way For Worst Fading Month (wfm)	5.6 sec
Outage, 1-Way, Non-Diversity (wfm)	2399 sec
Rcv Diversity Improvement , $S_r = 10$ meters	12.2
Outage, 1-Way, 2-Path Space Diversity,	197 sec
Trmt Diversity Improvement, $S_t = 10$ meters	147
Outage, 1-Way, Quad-Path Diversity	1.4 sec

The 2-path receive space diversity design misses the outage objective by a factor of 37. With quad-path diversity, the result outage is less than the objective by a factor 4.

